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Influences of edaphoclimatic conditions on deep rooting and soil water availability in Brazilian *Eucalyptus* plantations

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ABSTRACT

Brazilian roundwood industry is one of the most important and productive in the world, with *Eucalyptus* plantations alone representing 73% of the total planted forests. Deep rooting in these plantations represents a more common phenomena than generally expected. However, there is still a lack of information on environmental factors that drive root growth in deep soil layers, with particular emphasis on edaphoclimatic conditions, and related consequence in terms of soil water behavior. As a part of a larger project, this research aimed to investigate soil water and fine root system distribution in deep tropical soils under a commercial *Eucalyptus* plantation chronosequence. Along a 2800-km gradient (from south- to north-east Brazil), 14 experimental areas were planted with a "plastic" clone (*E. urophylla*) and investigated in terms of climatic conditions, soil and water features, and plant/stand development for an entire 6-years rotation period. Fine roots distribution were investigated in one site (in Brazil) till to 20 m deep at 3, 9, 24, 48, and 65 months after planting. Results showed a fast displacement of the root front down to 75, 325, 825, 1250, and 1575 cm at month 3, 9, 24, 48, and 65 after planting, respectively. Fine root densities (g cm^{-3}) and proportional water capture exponentially decreased with soil depth. Deep fine roots showed a relativelly higher efficiency in acquiring water than the shallower, denser roots. The relationship between stand height *vs* root front depth followed an exponential trend, suggesting that these stands developed relatively faster in height rather than in depth during the first 48 months, with the opposite characterizing plantation afterwards. Regardless of stand age, *E. urophylla* trees rapidly explored a considerable volume of soil at a relatively limited carbon cost. Multivariate statistics showed that edaphoclimatic conditions play a major role in *Eucalyptus* plant/stand development. This study outlined the major role played by soil development. From poorly developed sandy Entisols, to medium developed Inceptisols, and to most developed fine textured Oxisols, both plant growth and stand productivity greatly improved accordingly. This study suggests that soil type, together with other environmental factors, are likely to influence both the development and behavior of *Eucalyptus* plantations for an extent greater than commonly anticipated.

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1. Introduction

Brazilian planted tree industry is a world leader in timber production for pulp, fiber, wood, energy, and many other common and/or new applications (FAO, 2019). The total area of planted forests for industrial purposes reached 7.84 million hectares in 2016, a growth of 0.5% in just one year. This increase was exclusively due to *Eucalyptus* plantation. With 5.7 million hectares, *Eucalyptus* plantations represent 73% of the total planted forests in the country and 29% of the *Eucalyptus* forests worldwide (IBÁ, 2017). *Eucalyptus* plantations in Brazil covered just 1% of the total national territory, but they are responsible for (IBÁ, 2017): *i*) 91% of all the wood used for productive purposes in the country; *ii*) 6.2% of the Brazilian GDP, and; *iii*) 3.7 million of employers involved in forest activity (direct, indirect, and income-effect). There are economic reasons justifying the great importance of *Eucalyptus* plantations. However, this represents multiple challenges in the perspective of a new green economy, sustainable forest management, ecosystem protection, soil conservation, greenhouse gases mitigation, etc. Additionally, forest plantations play a major role in decreasing the pressure, with related negative impacts, on natural ones since it has been demonstrated that they reduced harvesting from natural forests by 26%–35% (Buongiorno and Zhu, 2014; Nepal et al., 2019).

Eucalyptus planted forests are mostly located in the states of Minas Gerais (24%), São Paulo (17%), and Mato Grosso do Sul (15%) where, at 5.5 years in plantation age, wood biomass can reach very high levels in irrigated plots, such as 141 Mg ha^{-1} (Stape et al., 2010). In all these areas water management can play a pivotal role in the commercial success of the plantation. Indeed, the pedoenvironment is characterized by deep, sandy, infertile, strongly leached acidic soils (Abreu-Junior et al., 2017) that in combination with climatic conditions (high mean temperature) can favour a rapid soil drying. Such phenomena can cause severe plant thermal stresses responsible for irreversible eco-physiological issues of plants and the entire plantation. Moreover, in order to sustain, or even increase, the high rates of *Eucalyptus* growth in the near future additional concerns must be carefully taken into account, such as: *i*) changes in climatic conditions, with a foresee increase in drought periods due to an increasing trend in mean temperature and a decreasing one in mean precipitations (Germon et al., 2019); *ii*) an increase in exotic pest/disease diffusion (Wingfield et al., 2013). Increasing knowledges about soil water distribution along the deep tropical soils represents a key step towards an improvement in the management of *Eucalyptus* plantations.

Among factors influencing soil water use by planted trees and crops in general, fine root densities and distribution along the soil profile are of primary importance because they determine the amount of water available to the plants (Ferchaud et al., 2015). Even if there is growing evidence suggesting that deep rooting could be more widespread among plant species in tropical regions than generally expected, there is still a lack of information on environmental factors driving root growth into deep soil layers (Christina et al., 2017). This was also due to the well-known difficulty in investigating such deep pedotypes and annexed complex root systems (Ferchaud et al., 2015; Freycon et al., 2015). Additionally, frequent approximations on important soil water parameters for *Eucalyptus* cultivation are often reported without any reference to the root system (Binkley et al., 2019).

The root system is the main means of plants to access nutrient and water resources in the pedosystem. Root structure is determined primarily by genetic attributes, but its development can be strongly affected by edaphoclimatic features, i.e., soil physical-chemical characteristics and climatic conditions (Plasencia et al., 2016). The root system is well known for its considerable plasticity and hence its role in plant adaptation to adverse conditions, including drought and low natural soil fertility (Pierik and Testerink, 2014). From this point of view, water uptake by deep roots is an effective means of plants' adaptation to drought in tropical and subtropical forests (Christina et al., 2017). Soil depth and development can exert a great influence on root system since trees can absorb water and nutrients from deep soil horizons. In tropical areas, where the climate is characterized by high evapotranspiration phenomena and a well-defined dry period, water and nutrient uptake by roots in deep horizons may increase the survival rate of the trees during prolonged drought periods, thus increasing wood production (Paz, 2003; Padilla and Pugnaire, 2007). Studies on soil water uptake and root distribution along soil profile are usually restricted to a specific, predefined plant development stage and with soil samples collected only along the first few meters (Ferchaud et al., 2015). However, a recent study in a throughfall exclusion experiment showed that management practices in *Eucalyptus* plantations as well as the rainfall regime can greatly influence soil water storage down to a depth of 17 m and tree growth (Christina et al., 2018). Additionally, questions concerning soil type and development have been rarely considered. In the case of tropical *Eucalyptus* plantation, deep soils (> 200 cm) are common with a large range of degrees of development and commercial plantations are characterized by longer rotation cycles than most common crops. There is a lack of *in situ* measurements investigating the multiple interactions between climate, soil features, soil water, and plant/stand vertical growth.

The objective of this research was to gain insight into soil water contents and fine root distributions in deep tropical soils under a commercial *Eucalyptus* plantation chronosequence. In order to understand how climatic and soil conditions influence soil water, root and plant/stand development, several experiments were conducted along a 2800-km gradient (south- to north-east Brazil) characterized by different environmental conditions. In particular: *i*) edaphoclimatic conditions and plant/stand development were investigated in 14 sites, where just one kind of *Eucalyptus* clone was planted (*Eucalyptus urophylla* S.T. Blake, hereafter *E. urophylla*) and selected for its well-known plasticity for different environmental conditions; *ii*) fine roots were investigated in one site along a chronosequence of 3, 9, 24, 48, and 65 months after planting.

2. Materials and methods

The TECHS Project (Tolerance of *Eucalyptus* Clones to Hydric, Thermal and Biotic Stresses, www.ipef.br/techs/en) started in 2011 aiming to investigate how hydric, thermal, and biotic stresses together with spacing and genetics could influence survival and growth of *Eucalyptus* trees at both individual and stand level (Binkley et al., 2019). It was a large experimental research platform involving several forest companies, universities, and research institutions collaborating in the investigation of 36 experimental sites located across a 3500-km gradient from the Amazon Region to Uruguay. Several experiments on both basic and applied science in *Eucalyptus* plantation and management were carried out. For the sake of brevity, in this paper the experiment about soil water and root distribution would be presented only.

2.1. Site selection

As previously reported, a large gradient in environmental conditions was investigated during the TECHS Project. As a matter of fact, environmental conditions varied from "warmer Tropical sites" (WTS) to "cooler Subtropical sites" (CSS). Additionally, 18 clones of *Eucalyptus*, carefully selected by a group of breeders involved in the project, were planted. These were selected and planted as: *i*) 4 clones as suitable for a wide range of environmental conditions ("plastic" clones), planted across all 36 TECHS sites; *ii*) 7 clones as suitable for warmer conditions, planted at the WTS only; *iii*) 7 clones as suitable for cooler conditions, planted at the CSS only. All these clones were representative of the different genetic materials used by forest industry in Brazil and were characterized by different susceptibility to water and thermal stresses.

Results in this paper come from experiments carried out in the sites where "plastic" clones were planted. In particular: *i*) 14 sites selected to

Table 1
Main features of selected TECHS sites for investigation of soil, water, and other hydrological parameters.

TECHS site[a]	Altitude (m a.s.l.)	Municipality, State[b]	T (°C), P (mm)[c]	PET, AET (mm)[d]	AI[e], CC[f]	Soil Order[g]	MSH[h]
2AR	770	Arapoti, PR	18.4, 1436	569, 562	Super humid, Cwb	Oxisol	A_p-B_{o1}-B_{o2}-…
4BO	243	Belo Oriente, MG	23.0, 1065	1002, 828	Humid, Aw	Oxisol	A_p-B_{o1}-B_{o2}-…
5GU	873	Guanhães, MG	21.0, 1013	796, 704	Humid, As	Oxisol	A_p-B_{o1}-B_{o2}-…
7RV	681	Rio Verde, GO	23.2, 1319	1036, 724	Humid, Aw	Entisol	A_p-C_1-C_2-…
9ES	969	Estrela do Sul, MG	23.5, 1334	1067, 928	Humid, Aw	Oxisol	A_p-B_{o1}-B_{o2}-…
10BO	869	Botucatu, SP	21.4, 1332	842, 783	Humid, Aw	Oxisol	A_p-B_{o1}-B_{o2}-…
11CS	783	Chapadão do Sul, MS	22.8, 1154	983, 780	Humid, Aw	Oxisol	A_p-B_{o1}-B_{o2}-…
14IN	480	Inocência, MS	24.3, 1026	1188, 916	Sub-humid, Aw	Entisol	A_p-C_1-C_2-…
20MG	633	Mogi Guaçu, SP	22.3, 1255	942, 867	Humid, Aw	Oxisol	A_p-B_{o1}-B_{o2}-…
22TB	888	Telêmaco Borba, PR	17.8, 1436	569, 561	Super humid, Cwb	Oxisol	A_p-B_{o1}-B_{o2}-…
23OC	870	Otacílio Costa, SC	17.1, 1525	481, 476	Super humid, Cfa	Inceptisol	A_p-B_{w1}-B_{w2}-…
24BO	656	Borebi, SP	22.0, 1116	908, 800	Humid, Aw	Entisol	A_p-C_1-C_2-…
29US	81	Urbano Santos, MA	27.5, 878	1492, 656	Sub-humid, Aw	Entisol	A_p-C_1-C_2-…
33BU	695	Buri, SP	20.0, 1196	662, 645	Humid, Cwb	Oxisol	A_p-B_{o1}-B_{o2}-…

[a] TECHS site acronyms assigned according to numbero of site and municipality (for instance, 2AR means the site number 2 belonging to the Arapoti municipality).
[b] Brazilian States of MG = Minas Gerais; PR = Paraná; RS = Rio Grande do Sul; GO = Góias; SP = São Paulo; MS = Mato Grosso do Sul; TO = Tocantins; SC = Santa Catarina; MA = Maranhão.
[c] In terms of mean annual temperature and rainfall.
[d] Potential and actual evapotranspiration.
[e] Aridity index.
[f] Climatic classification (Köppen, 1936).
[g] According to Soil Taxonomy (2014).
[h] Main soil horizons.

investigate the relationships between climatic conditions, soil and water features together with related hydrological parameters, and plant/stand development; *ii*) one site (Site code "14IN"; *E. urophylla* plantation; Clones A1; Inocência, State of Mato Grosso do Sul, central-western Brazil, Table 1) was selected to investigate root development along a chronosequence of 3, 9, 24, 48, and 65 months after planting. These 14 sites, located along a 2800-km gradient with contrasting latitudes and altitudes, were selected to cover a wide range of climatic and soil conditions in *Eucalyptus* plantations (Table 1). Clone A1 of the *E. urophylla* species was selected as typically representing "plastic" clones, i.e., those suitable to be planted along a wide range of environmental conditions, and for being one of the most planted clones in Brazil. Chronosequence was chosen to investigate the entire commercial rotation period for *Eucalyptus* in Brazil (65–72 months). From this point of view, we selected the post-planting (3 months), intermediate (9, 24, 48) and last step in the rotation cycle.

2.2. Experimental design

The experiment started at the end of 2011 and beginning of 2012. Plantations were organized in plots of 90 × 24 m, with 8 lines constituted by 30 trees (3 m distance between each line and tree; Fig. 1a). Every plot was then divided into 4 sub-plots where different experiments were conducted. For the purposes of the present study, the subplot was 30 × 24 m (Fig. 1b). The length of rotation period was 6 years, conventionally used for *Eucalyptus* plantation in Brazil.

Soil preparation was performed according to usual Brazilian forest companies' operational activities. Soil was tilled down to 40/50 cm deep. Irrigation time and water amounts varied according to the seedlings' needs conditioned by the site features. Three to 4 L of water per seedling were applied without a predetermined irrigation frequency but rather according to plant need.

Soil nutrient contents were estimated prior to experiment (end of 2011) by analyzing soil surface horizons. Then, an additional fertilizers of 10% relative to commonly recommended dose was applied to all the TECHS sites to avoid any nutritional deficiency over the entire experiment period. Consequently, fertilizers were applied to each plot during the first year as: 70 kg ha^{-1} of N, 45 kg ha^{-1} of P, 85 kg ha^{-1} of K, 500 kg ha^{-1} of Ca, 90 kg ha^{-1} of Mg, 40 kg ha^{-1} of S, 3 kg ha^{-1} of B, 1 kg ha^{-1} of Cu, and 1 kg ha^{-1} of Zn. Fertilization schedule varied among the sites, with the total amount distributed in 2–4 applications starting from the pre-planting period to the twelfth month. Herbicides were applied to keep the plots weed-free. In particular, Glyphosate (Scout®) and Isoxaflutole (Fordor®) were applied with the first application along planting lines in 30–40 days after planting. The second application was conducted, where necessary, 60/70 days after planting. After this, additional applications were performed according to weed conditions.

2.3. Data collection

The data consisted of: *i*) climatic parameters collected by a permanent daily-recording weather station installed in all of the 14 sites; *ii*) soil and hydrologic parameters collected and measured immediately before the end of the rotation age (6 years, *vide supra*) in all of the 14 sites; *iii*) fine root investigation along a chronosequence of 3, 9, 24, 48, and 65 months after planting, at the TECHS site "14IN" only (Table 1); and *iv*) dendrometric measurements conducted every 6 months from the beginning of the experiment to the end of the rotation, for all of the 14 sites. In the following sections all of these steps were carefully described.

2.3.1. Climatic parameters

A weather station was installed at each TECHS site, for daily recording of temperature (T) and rainfall (P). Potential and actual evapotranspiration (PET, AET) were calculated according to Penman-Monteith method (Monteith, 1965), climate classified according to Köppen (1936), and aridity index evaluated through the P/PET rate.

2.3.2. Soil sampling, analysis, and hydrologic measurements

Soil samples were collected, in all of the 14 sites, at the plantation age of 5.5 years (2017), i.e., six months before the end of crop rotation (6 years). Trenches of 2 m depth, 1.2 m width, and 1.5 m length were dug in the central area of the experiment (corresponding to the center of Fig. 1b) to fully investigate the soil profile. They were then described with the identification of genetic horizons and soils classified accordingly (Soil Survey Staff, 2014). As reported in Table 1, three different main pedotypes have been investigated: Entisols, Inceptisols, and Oxisols. The parameter "soil development" (SD) was calculated according to the soil sequence Entisols → Inceptisols → Oxisols, scoring poorly

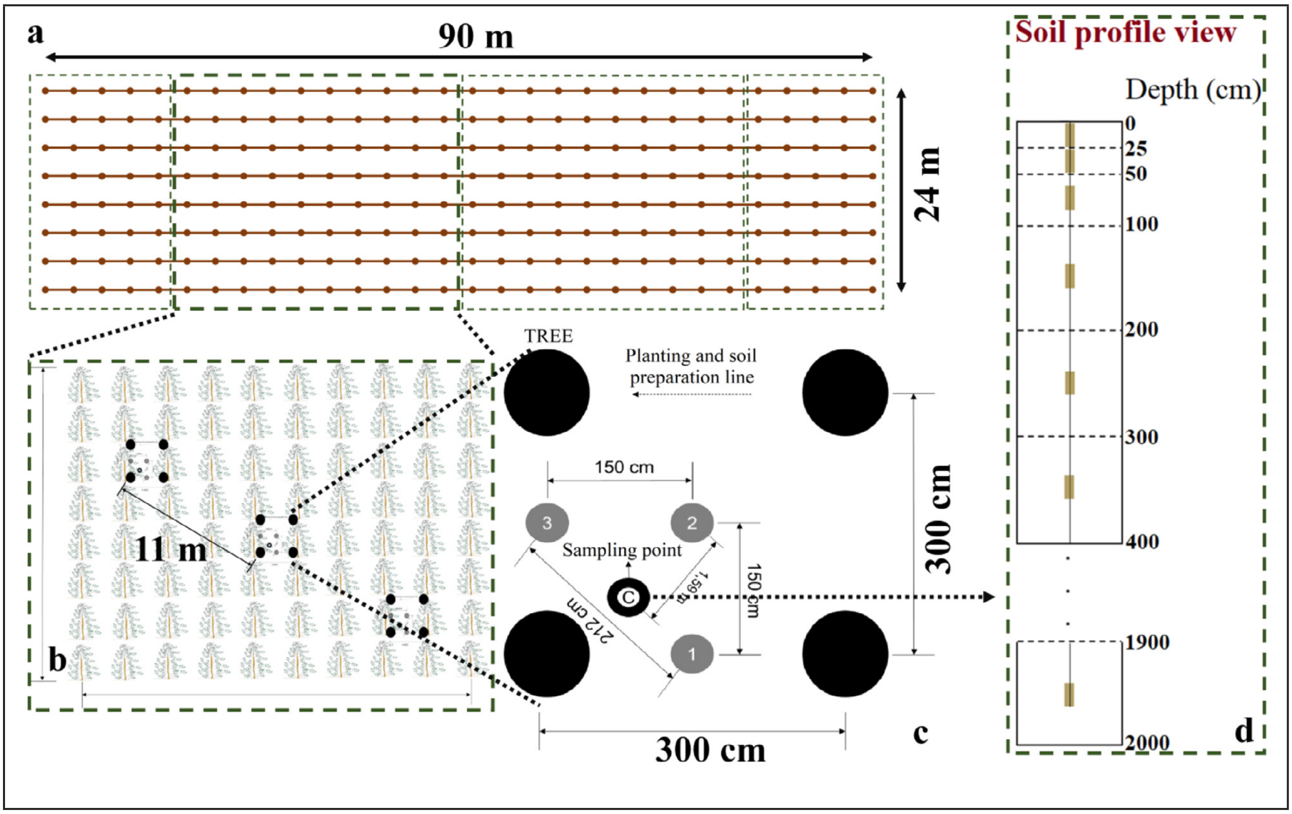

Fig. 1. Schematic representation of *E. urophylla* plantation with plant (a), soil (b), and roots (c and d) sampling plans.

developed Entisols with the lowest value, while most developed Oxisols with the highest one; Inceptisols were scored with medium values representing transitional phases.

Undisturbed soil samples were collected using an Uhland soil sampler (3 samples for each horizon) from both surface mineral A_p and B (B_o or B_w) or C horizons, depending on the soil type (Table 1).

All soil analyses (Table 2) were performed according to official methods in Brazil (EMBRAPA, 1997). Sand (2.0–0.02 mm), silt (0.02–0.002 mm), and clay (< 0.002 mm) fractions were separated with the densimeter method following pre-treatment with H_2O_2 and sodium hexametaphosphate. Soil pH-H_2O was measured potentiometrically with a glass electrode in a soil/water mixture of 1:2.5. Soil organic matter (SOM) content was estimated by the Walkley-Black method. Cation-exchange capacity (CEC) was determined via saturation with KCl. The soil particle density (PD) was determined by the flask method, while soil bulk density (BD) with the metal cylinder. Total porosity (TP) was then calculated as:

$$TP\,(m^3\,m^{-3}) = 1 - (BD/PD) \quad (1)$$

Table 2
Main soil physical-chemical features (mean ± st. err).

TECHS site[a]	pH-H_2O	Sand	Silt	Clay	BD[b]	PD[c]	TP[d]	SOM[e]	CEC[f]
		(%)			(g cm^{-3})		($m^3\,m^{-3}$)	(g dm^{-3})	($mmol_c\,kg^{-1}$)
2AR	4.1 ± 0.0	9 ± 0	15 ± 0	76 ± 0	1.1 ± 0.0	2.6 ± 0.1	0.6 ± 0.0	36 ± 0	92 ± 1
4BO	4.1 ± 0.0	39 ± 1	3 ± 0	58 ± 1	1.1 ± 0.0	2.5 ± 0.0	0.6 ± 0.0	35 ± 0	62 ± 0
5GU	3.9 ± 0.0	39 ± 1	4 ± 0	57 ± 1	1.3 ± 0.1	2.6 ± 0.1	0.5 ± 0.0	41 ± 1	92 ± 1
7RV	4.5 ± 0.0	87 ± 0	2 ± 0	11 ± 0	1.5 ± 0.1	2.7 ± 0.1	0.5 ± 0.0	19 ± 0	36 ± 0
9ES	3.9 ± 0.0	12 ± 0	5 ± 0	83 ± 0	0.9 ± 0.0	2.5 ± 0.0	0.6 ± 0.0	43 ± 1	89 ± 1
10BO	4.3 ± 0.0	75 ± 0	3 ± 0	22 ± 0	1.4 ± 0.1	2.7 ± 0.1	0.5 ± 0.0	30 ± 0	67 ± 0
11CS	4.3 ± 0.0	72 ± 0	1 ± 0	27 ± 0	1.5 ± 0.1	2.7 ± 0.1	0.4 ± 0.0	24 ± 0	55 ± 0
14IN	4.1 ± 0.0	84 ± 0	3 ± 0	13 ± 0	1.6 ± 0.1	2.7 ± 0.1	0.4 ± 0.0	11 ± 0	65 ± 0
20MG	4.1 ± 0.0	44 ± 1	5 ± 0	51 ± 1	1.3 ± 0.1	2.6 ± 0.1	0.5 ± 0.0	34 ± 0	97 ± 1
22TB	4.0 ± 0.0	21 ± 0	12 ± 0	67 ± 0	1.1 ± 0.0	2.5 ± 0.0	0.6 ± 0.0	52 ± 1	184 ± 2
23OC	3.9 ± 0.0	24 ± 0	20 ± 0	56 ± 0	1.1 ± 0.0	2.5 ± 0.0	0.6 ± 0.0	45 ± 1	338 ± 3
24BO	4.6 ± 0.0	87 ± 0	3 ± 0	10 ± 0	1.3 ± 0.1	2.8 ± 0.1	0.5 ± 0.0	12 ± 0	105 ± 2
29US	4.1 ± 0.0	74 ± 1	5 ± 0	21 ± 1	1.6 ± 0.1	2.7 ± 0.1	0.4 ± 0.0	16 ± 0	91 ± 1
33BU	4.1 ± 0.0	27 ± 0	13 ± 0	60 ± 1	1.0 ± 0.0	2.6 ± 0.0	0.6 ± 0.0	28 ± 0	111 ± 2

[a] Legend as in Table 1.
[b] Bulk bensity.
[c] Particle density.
[d] Total porosity.
[e] Soil organic matter.
[f] Cation-exchange capacity.

Table 3
Main soil hydrologic features (mean ± st. err).

TECHS site[a]	AWC[b] (mm)	SWS[c]	SWD[d]	SWP[e]
2AR	153 ± 10	2481 ± 156	7 ± 0	874 ± 55
4BO	107 ± 3	1125 ± 34	174 ± 5	263 ± 8
5GU	138 ± 6	1223 ± 53	92 ± 4	309 ± 13
7RV	57 ± 2	325 ± 9	312 ± 9	606 ± 18
9ES	66 ± 1	1727 ± 18	139 ± 1	427 ± 4
10BO	77 ± 2	865 ± 23	58 ± 2	549 ± 15
11CS	99 ± 3	491 ± 13	203 ± 5	387 ± 10
14IN	80 ± 2	404 ± 8	272 ± 6	110 ± 2
20MG	123 ± 8	1341 ± 85	75 ± 5	404 ± 25
22TB	155 ± 9	2250 ± 128	7 ± 0	874 ± 50
23OC	191 ± 4	2123 ± 45	5 ± 0	1049 ± 22
24BO	78 ± 3	404 ± 13	109 ± 4	317 ± 10
29US	242 ± 7	257 ± 7	836 ± 23	222 ± 6
33BU	135 ± 3	1987 ± 50	17 ± 0	551 ± 14

[a] Legend as in Table 1.
[b] Available water content/capacity.
[c] Soil water storage.
[d] Soil water deficit.
[e] Soil water surplus.

All the collected undisturbed samples (Table 3) were subjected to two different loads to determine permanent wilting point (PWP; −1500 kPa) and field capacity (FC; −10 kPa). The available water capacity (AWC) in a specific soil layer was then calculated as:

$$AWC\,(\mathrm{mm}) = (((\theta_{FC} \times BD) - (\theta_{PWP} \times BD)) \times BD \times 10) \times SD \quad (2)$$

where:

θ_{FC} = soil water content at field capacity on a mass basis (kg kg^{-1}).
θ_{PWP} = soil water content at permanent wilting point on a mass basis (kg kg^{-1}).
BD = soil bulk density (g dm^{-3}).
SD = thickness of the soil layer (m).

AWC was then used to calculate soil water storage (SWS), soil water deficit (SWD) and soil water surplus (SWP) according to methods proposed by Rolim et al. (1998).

2.3.3. Root sampling and measurements

Fine roots (Ø < 2 mm) were sampled in the TECHS site “14IN” only, where the “plastic” A1 clone was planted. The root system was sampled and evaluated at months 3, 9, 24, 48, and 65 in a chronosequence of plantations to cover a complete rotation cycle.

The sampling points were located as reported in Fig. 1c. This approach was chosen to collect roots not too far/near from the trunk. Indeed, selected sampling points were located along the main direction of planting line and, accordingly root development. Roots were always collected at the end of the rainy season (May–June) to ensure high soil humidity and a peak in root uptake of soil water. Core drill samples (Fig. 1c) were collected by a gasoline powered soil sampler with a drill diameter of 100 mm. Samples were collected at the fixed depths of 0–25, 25–50, 50–100, 100–150 cm and then every 50 cm until no roots were found (Fig. 1d). Three core drills were realized in each plot for each of the investigated (months 3, 9, 24, 48, and 65) plant development (Fig. 1c).

Samples were immediately stored in plastic bags to avoid soil moisture loss and stored in the refrigerator to avoid root decay. Only living fine roots (Ø < 2 mm) were investigated since they are considered as those primarily involved in water and nutrient uptake (Christina et al., 2011). Before measuring root length and biomass, living roots were distinguished from dead one on the basis of color, brittleness, structure of cortex or bark and color of stele or xylem. Two sieves of 300 and 500 µm mesh were then used to separate roots smaller and greater than 1 cm, respectively. Roots were then dried for 72 h at 65 °C and weighed to determine dry biomass. Soil moisture in each horizon was measured from 20 g of soil dried at 105 °C for 72 h up to constant weight. Dry masses separated in the laboratory (estimated proportionally to the mass of the total soil sample collected) were totalized for each soil layer, thus calculating the fine roots density (FRD, in g cm^{-3}). The model proposed by Witschoreck et al. (2003) was used to convert FRD in root length density (RLD), i.e., the total root length per unit of soil volume (Gregory, 2006).

2.3.4. Relationship between fine root density and proportional water capture

Modeling of water absorption by the root system was performed taking into account contrasting climatic conditions and soil physical features characterizing the 14 investigated sites (*vide supra*) as the experiment encompassed several sites with different edaphoclimatic conditions. Consequently, generated models were considered to cover a wide range of edaphoclimatic conditions.

As demonstrated by Ferchaud et al. (2015) RLD can be used as an indicator of root intersection density (RID), i.e., the mean number of root impacts per cm^2. As a matter of fact, RLD and RID are characterized by a linear relationship. Consequently, the relationship between RLD and the proportional water capture (PWC) was calculated by the model originally proposed by King et al. (2003) and modified by Ferchaud et al. (2015):

$$PWC\,(\%) = (\alpha - y_o) \times (1 - e^{-RLD\,k}) + y_o \quad (3)$$

where:

a is the highest PWC achievable by the crop (a = 100% in the original model).
y_o is the PWC obtained in free root soil layers due to possible water capillary rise ($y_O = 0$ in the original model).
k is a “resource capture coefficient” summarizing details of both water uptake physiology and soil water transport. A higher k-value leads to a faster increase in the extraction of water when the root density increases.

A common value for all planting ages was chosen for y_o and the optimization of the parameters for a and k was performed with the Excel Solver using the non-linear Generalized Reduced Gradient (GRG) method. The minimized criterion was root mean square error (RMSE).

Root growth rate (RGR) was calculated as the ratio between the depth reached by root (cm) at the investigation time (days).

The available amount of water for planting (AWP) at months 3, 9, 24, 48, and 65 was calculated from the PWC and AWC values, as a function of RLD and the depth (D) of the soil layer, as:

$$AWP_{3,9,24,48,65\,months} = AWC_{1\,\mathrm{m}} \times PWC \times D \quad (4)$$

where:

i = is the investigated soil layer which varied according to the plant age at which it was calculated. The first layer was standardized at the 0–25 cm (as shown in Fig. 1d).
AWC_{1m} = is the standardized soil available water capacity at 1 m deep, measured in collected undisturbed soil sample.
D = is effective soil depth as a function of planting age (75, 325, 825, 1250, and 1575 cm at 3, 9, 24, 48, and 65 months, respectively)

2.3.5. Dendrometric measurements

Tree growth was assessed by measuring the height (H) and the diameter at breast height (DBH) every 6 months, up to the sixth years (end of crop rotation), for each of the 80 trees characterizing the investigated sub-plot in all of the 14 TECHS sites (Fig. 1a, b).

The commercial volume of wood with bark was calculated using

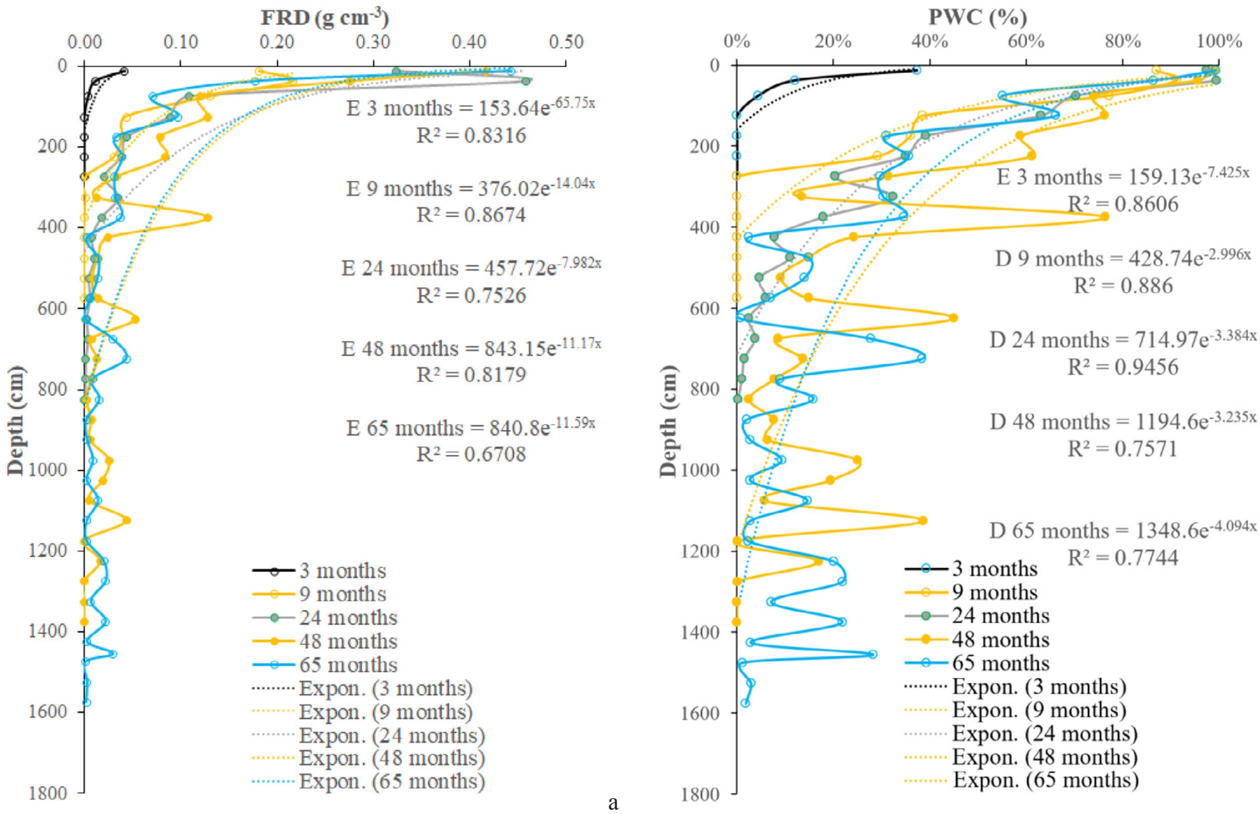

Fig. 2. Fine root density (FRD) and proportional water capture (PWC) distribution along the 20 m depth soil profiles sampled at 3, 9, 24, 48, and 65 months after planting.

volumetric models based on widely used volume equations already calibrated for *Eucalyptus* sp. with the stocking density used at the study sites. The model was calibrated using equations provided by Eldorado Brasil Celulose SA, by adjusting the Chapman-Richards model (Pienaar and Turnbull, 1973). As previously reported, the age of 6 years was selected since it is conventionally considered the rotation period for *Eucalyptus* plantation in Brazil, a standardization procedure of the mean annual increment (MAI) recorded in each of the 14 investigated sites was used. A guide curve method was applied according to the equation:

$$MAI_{6y}\,(\mathrm{m^3\,ha^{-1}\,year^{-1}}) = y \times MAI_y \times 265.6 \times e^{-1.56-0.58y} \times 256.6 \times e^{-1.56-0.58\times6}/6 \quad (5)$$

where:

y is stand age expressed in years, MAI_{6y} is mean annual increment at 6 years of age, and MAI_y is mean annual increment at the survey age.

In order to estimate wood biomass and quality together with their reationships with edaphoclimatic conditions, the basic wood density (BWD, g cm^{-3}) was determined by collecting cross-sectional disks from plants and then following the water displacement method (ABNT, 2003). Each disk was immersed into a vessel fully filled with distilled water causing the water to overflow. The displaced water was collected and measured to determine the green volume of the disk. After the disk was dried at a temperature of 103 ± 2 °C until a constant weight. The basic density was determined by dividing the dry mass by its respective saturated volume.

2.4. Statistical analysis

Univariate and multivariate statistics were carried out using the software program R (RStudio Team, 2016). Data were compared using analysis of variance (ANOVA). Significant differences between mean values were determined using a Tukey's post-hoc honest significant difference test with $p < 0.05$. Correlation matrix (CM) was elaborated to understand relationships among investigated attributes. Pearson's product moment correlation coefficient was used for Box-Cox transformed data with statistical significance determined with the Student's *t*-test ($p < 0.05$). Factor analysis (FA) based on the correlation matrix (using Pearson's product moment correlation coefficient) was used to explain the variation in a multivariate dataset with as few factors as possible. For facilitation of the interpretation of results, varimax rotation was used (Capra et al., 2014) and significance fixed at $p < 0.05$.

When reported, values in this study indicate the mean ± standard error.

3. Results and discussion

3.1. Fine root density (FRD) and proportional water capture (PWC)

One of the main novelties of this investigation is the study on fine roots dynamics at the depths of more than 10 m, which is rarely reported (Laclau et al., 2013; Lambais et al., 2017). Few tree species were characterized by roots growing more than 10 m deep, with limited results suggesting that the maximum rooting depth is underestimated in the tropical woody ecosystems (Christina et al., 2011). For such reasons there is an urgent need to sample soils down to the maximum root front (Schenk and Jackson, 2002). Recently, Germon et al. (2019) studied fine roots dynamics (*Eucalyptus grandis* W. Hill ex Maiden) down to 17 m depth and found fine roots along the whole profile in a young coppice, at 7.5 years after planting. However, as far as we are aware, soil water and fine root dynamics have never been investigated down to 20 m depth. Additionally, the maximum depth that can be reached in *E. urophylla* commercial plantations after a complete rotation cycle remains unknown.

All the fine root densities (FRD) in the chronosequence series (months 3, 9, 24, 48, and 65; Fig. 2a) showed a fast displacement of the root front down to deep soil layers. After just 3 months, roots had already reached the bottom of the A_p horizon and the first 30 cm of the first deep C_1 horizon. Overall, root front depth reached maximum values of 75, 325, 825, 1250, and 1575 cm at 3, 9, 24, 48, and 65 months after planting, respectively. Christina et al. (2017) explained such a fast colonization of deep soil layers as a "drought-avoidance strategy" allowing plants to access large amounts of soil water mainly during the early growth stage. Additionally, this behavior could represent a key factor that leads to the peak of biomass productions generally recorded during the second year after planting in Brazilian *Eucalyptus* commercial plantations (Stape et al., 2010).

For all the sampling ages, fine root density (FRD) exponentially decreased with depth (Fig. 2a) with the highest value ($0.46\ g\ dm^{-3}$) observed in the sub-surface layer (25–50 cm) at 24 months after planting. The highest FRD values were always observed in surface and sub-surface A_p horizons. Although depths > 8 m were already explored by fine roots 24 months after planting, the rooting depth corresponding to 80 and 90% of the fine root mass remained at the depths < 2.5 and 5.5 m throughout stand growth, respectively.

For the first time, this study recorded the maximum root front depth reached by fine roots in *E. urophylla* commercial plantation at the end of crop rotation. Indeed, the recorded value (1575 cm after 62 months of growth) have been ascertained for sure since core drill samples were taken down to a depth of 20 m with no roots found deeper. The exploration of deep soil layers has already been reported for other *Eucalyptus* species with roots growing faster (Christina et al., 2017), similar (Christina et al., 2011; Pinheiro et al., 2016) or slower (Robinson et al., 2006) than in our study.

Proportional water capture (PWC) ranged from 1% to 99% with higher values always reached in surface A_p horizons after 48 months (Fig. 2b). Generally speaking, PWC values decreased with soil depth even if such a tendency was not linear. The mean PWCs at the ages of 3, 9, 24, 48, and 65 months were 18%, 60%, 28%, 29%, 22%, respectively. PWC is generally calculated along the first few soil meters (1.5–2.5 m) (King et al., 2003; Ferchaud et al., 2015). Quantifications of soil water storage in very deep soil profiles are rare in *Eucalyptus* plantations (Smethurst et al., 2015; Christina et al., 2018). This is often related to the fact that such kind of deep investigations pose serious difficulties in terms of field methods and related costs. Consequently, strong underestimations in PWC values are usually reported (Jackson et al., 2000; Markewitz et al., 2010; Freycon et al., 2015). As a matter of fact, our results showed that in deep layers PWC could be greater than expected. For example, at 1125 cm soil depth 39% of PWC was observed at the age 48 months, while at 1445 cm a PWC of 28% was observed at 65 months of age (Fig. 2b). Such values clearly show the importance of water absorption by fine roots in very deep soil layers. A higher capacity of deep roots than shallow roots to take up cations has already been shown in *Eucalyptus* plantations (da Silva et al., 2011). Thus, even if root density can often represent a limiting factor for extracting water, deep finer roots have however the capacity to withdraw large amounts of water. Such an outcome was observed for several other crops (Robertson et al., 1993; Zhang et al., 2004) and generally explained as a reduced efficiency in water absorption by denser root systems due to increased competition among neighboring roots. Overall, all previously reported data are consistent with the well-known dual root system characterizing *Eucalyptus* plants (Canadell and Zedler, 1995) and consisting of a dense fine root network in the upper soil layers *vs* a finer, scattered fine root distribution in deep soil layers. A modeling approach carried out over an entire *Eucalyptus* rotation in Brazil showed that fine root distribution plays a major rule in water uptake since: *i*) shallow lateral roots utilize water mainly coming from rainfall in the wet season; *ii*) deep roots take up the water stored in deep soil layers (from the previous wet season) during the dry period; and *iii*) even though soil water coming from rainfall can be affected by fast percolation in sandy soils, the deep rooting system avoids loosing this transient resource after canopy closure (Christina et al., 2017).

The high water absorption potential by *E. urophylla* shown in this study agrees with that reported by Christina et al. (2017) for *E. grandis*. As we observed in the present investigation, these researchers reported that strategies and processes for water absorption in *Eucalyptus* commercial plantations can be further depicted by: *i*) a rapid root growth after planting providing access to large amounts of water stored in deeper soil layers in the first 2 years; *ii*) a proportion of water absorption near the water table that can be much higher during the drought periods, although mean water withdrawal at the depths greater than 10 m represents only 5% of canopy transpiration at the planting age of 5 years; and, *iii*) a water table raising from a depth of 18 m before harvesting of the previous stand to a depth of 12 m at the age of 2 years and then falling again at the harvesting age, as the evapotranspiration rates exceeded the annual rainfall.

Other important questions can be raised by comparing root growth rates (RGR) *vs* PWC and FRD. RGR ranged from 0.83 (after 3 months), 1.30, (9 months), 1.18 (24 months), 0.87 (48 months), 0.81 (65 months) $cm\ day^{-1}$, thus quickly increasing along the first 9 months, and then decreasing to the values recorded at the beginning, with the stand age according to a polynomial trend (Fig. 3b). This data confirmed a fast exploration of root growth but with a clear decreasing trend as time went by. A slight decrease in root front velocity with stand age in *Eucalyptus* plantations have been already observed in Brazil (Christina et al., 2011; Laclau et al., 2013) and South Africa (Dye, 1996). Laclau et al. (2013) hypothized that this could be a result of substantial water withdrawal in the subsoil. These authors argued that a drop in soil water content in deep soil layers after canopy closure was not only due to the disruption of drainage from the upper soil layers but could be also caused by water withdrawal by tree roots. The strong relationship between RGR and PWC (Fig. 3) in our study seems to strongly confirm this hypothesis.

When comparing RGR with FRD additional important questions arise. Gonçalves (1995) found that RGR was inversely correlated with FRD in *Eucalyptus grandis* W. Hill ex Maiden plantation, thus at increasing FRD a decrease in RGR was observed. Recent minirhizotrons studies in *Eucalyptus* plantations also showed higher root elongation rates in very deep soil layers relative to the topsoil with maximum values for individual roots up to $3.5\ cm\ d^{-1}$ (Lambais et al., 2017; Germon et al., 2019). In our study the opposite was true since RGR and FRD were positively correlated (r = 0.919, $p < 0.001$), thus with increasing FRD the RGR increased accordingly. As a matter of fact, we observed high RGR values in deep layers too with a possible explanation related to the fact that in these sandy soils there was no physical osbstacle to limit root growth.

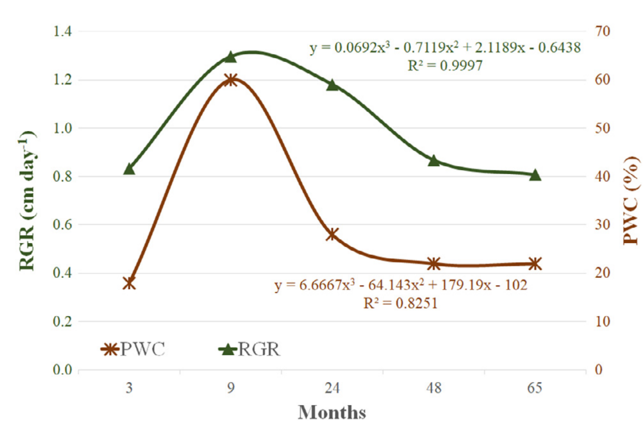

Fig. 3. Relationship between roots growth rate (RGR) *vs* PWC along the 3-, 9-, 24-, 48-, and 65-month chronosequence series. Equations shows polynomial trends of investigated parametrs.

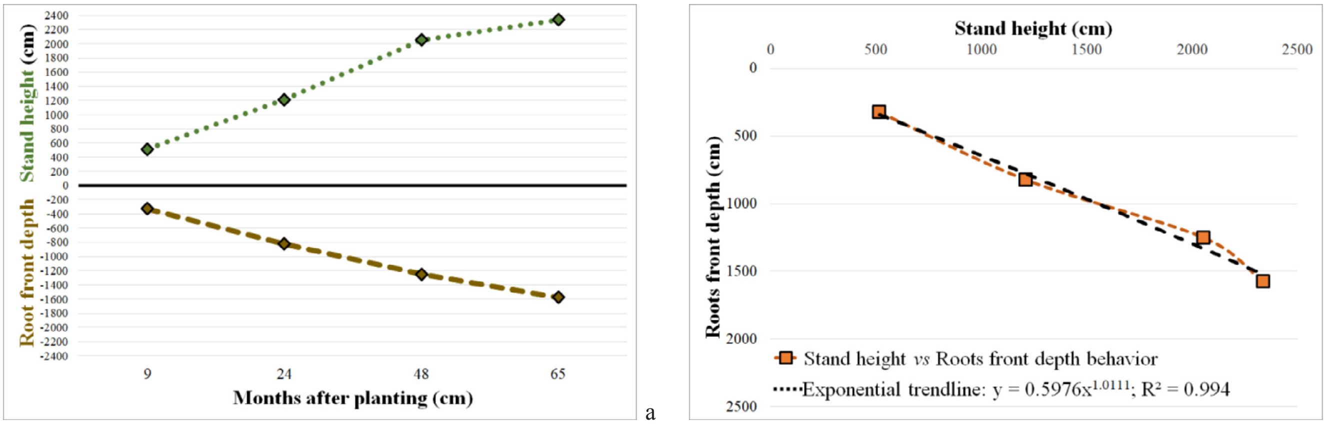

Fig. 4. Relationship between the stand height *vs* roots front depth: (a) along the 9-, 24-, 48-, and 65-month chronosequence series; (b) in terms of observed behavior (orange line) and related exponential fitted trendline (black line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Root front depth vs stand height

The root front depth compared to stand height in our chronsequence ranged from 61 to 68%, with a mean value of 65% (Fig. 4a). The root front depth and stand height increased following a similar pattern up to 48 months of age, with an almost symmetrical vertical growth rate. A general tendency towards synchrony between the vertical extension of shoots and roots throughout *Eucalyptus* growth was already documented (Christina et al., 2011); a pattern strongly dependent on fine roots biomass and reflecting plant strategies for environmental exploration for water and nutrient uptake. However, in our case, even if stand height *vs* root front depth could be well described by a linear trend ($R^2 = 0.987$, as in Christina et al. (2011)) an exponential function ($R^2 = 0.994$) could describe slightly better the observed relationship (Fig. 4b). This was not only related to an increased observed R^2, but rather from the observed root front depth *vs* stand height behavior along the investigated chronosequence series (Fig. 4a). As a matter of fact, with increasing stand height the root depth increased accordingly, but stand developed faster in height than in depth during the first 48 months rather than afterwards.

E. urophylla trees rapidly explored a considerable volume of soil at a relatively limited carbon cost. Indeed, regardless of the stand age, roots below the depth of 2 m amounted to < 20% of total fine root mass and decreased to < 10% below 6 m depth.

3.3. Influence of edaphoclimatic conditions on soil water and plant/stand development

3.3.1. Multivariate statistics

Correlation matrix (CM) showed several interesting correlations of high statistical significance (Table 4). Climatic parameters (T, P, and PET) strongly affect soil water content with the only exception of available water capacity (AWC) and available water for planting (AWP). With increasing mean T and a consequent increase in potential evapotranspiration (PET), both soil water storage (SWS; $r = -0.80$, $p < 0.001$) and surplus (SWP; $r = -0.84$, $p < 0.001$) decreased tremendously; thus leading to a strong increase in soil water deficit (SWD; $r = 0.84$, $p < 0.001$). An excessive increase in mean T and, consequently, PET negatively affected plant diameter (DBH: $r = -0.53$; $p < 0.05$), MAI_{6y} ($r = -0.47$; $p < 0.05$), and stand height ($r = -0.47$; $p < 0.05$). The sign of the correlations between mean rainfall (P) and all of other parameters was opposite compared to T but the correlations between P and DBH, root front depth (RFD) and MAI_{6y} were not significant. Several soil properties affected soil water resources and tree development. Soil development was highly correlated with soil water storage (SWS: $r = 0.63$, $p < 0.05$), soil water deficit (SWD: $r = -0.60$, $p < 0.05$), tree diameter (DBH: $r = 0.47$, $p < 0.05$), stand height (SH: $r = 0.57$, $p < 0.05$), and mean annual increment (MAI: $r = 0.49$, $p < 0.05$). This means that soil water storage increased in more developed Oxisols, while a concomitant decrease in soil water deficit can be observed. Additionally, Oxisols seem to positively affect even *Eucalyptus* stand height, wood diameter, and MAI_{6y}. Such multiple outcomes can be explained by simultaneously reading all the other correlation coefficients among soil parameters *vs* soil water and plant development. Indeed, the reasons why Oxisols can affect such parameters are because of this pedotype: *i)* finer fractions increases (silt and clay) while sand content decrease; and, consequently *ii)* the soil retains higher amounts of soil water and organic matter, thus alleviating water deficit issues and improving general soil physico-chemical conditions. Under such edaphic conditions, all plant and stand performance were strongly enhanced. All these aspects can be interpreted in the opposite direction for poorly developed sandy Entisols; these soils are affected by lower capability in terms of water storage (higher total porosity, lower bulk and particle density have been observed in these soils) while being characterized by higher issues in water deficit, all edaphic conditions that are relatively less favorable, as compared to Oxisols, for plant and the whole stand development.

In summary CM showed that edaphoclimatic conditions play a major role in *Eucalyptus* plant and stand development. An increase in mean T and, consequently, PET can result in: *i)* a decrease in soil water storage, consequantly increasing soil water deficit; and *ii)* a decrease in plant and stand growth rates.

The eigenvalues of the three extracted factors in the FA (factor analysis) after the matrix rotation were greater than 1, and these factors can, therefore, be grouped into a three-component model that accounts for 82% of all data variation (Fig. 5). In particular, F1 (Fig. 5a), representing 48% of the variance, showed soil development, clay and SOM content, and soil water storage (SWS) as all positively concordant while they were inversely correlated to pH and sand content. This factor confirmed, as previously explained by CM, that in those sites characterized by more developed, deeper and leached (pH decreased) pedotypes (Oxisols), clay and organic matter increased (with sand decreasing accordingly) thus contributing to improve soil water storage. Consequently, this factor can be interpreted as the "influence of soil development on soil water storage". F2 (accounting for 22% of the total variance, Fig. 5b) showed soil development and all plant/stand parameters (MAI6y, DBH, and SH) as all positively concordant, while all of these as inversely correlated with PET and SWD. This factor appeared to be strongly related to the previous one (F1). Indeed, it additionally showed that in Oxisols, due to the previous reported (in F1) favorable soil physical-chemical conditions that are able to decrease PET and water deficit, plant/stand performances were greatly improved. This

Table 4
Pearson coefficients for correlations of soil water (red acronyms: AWC, SWS, SWD, SWP, and AWP) and plant/stand parameters (black acronyms: DBH, SH, and MAI_{6y}) *vs.* edaphoclimatic conditions (grey background for climate; green for soil).

	AWC	SWS	SWD	SWP	AWP	DBH	SH	MAI_{6y}
T_{mean}	0.13	-0.80***	0.84***	-0.84***	-0.13	-0.53*	-0.47*	-0.63*
P_{mean}	-0.09	0.69**	-0.66*	0.90***	-0.09	0.26	0.37	0.37
PET	-0.08	-0.79***	0.87***	-0.81***	-0.08	-0.58*	-0.49*	-0.65*
Soil development	-0.02	0.63*	-0.60*	0.27	-0.02	0.47*	0.57*	0.49*
pH	-0.53*	-0.60*	0.10	-0.17	-0.53*	0.20	0.02	0.06
Sand	-0.32	-0.94***	0.51*	-0.56*	-0.32	-0.21	-0.36	-0.33
Silt	0.56*	0.82***	-0.40*	0.81***	0.56*	0.14	0.10	0.31
Clay	0.24	0.89***	-0.49*	0.45*	0.24	0.20	0.39	0.30
PD	-0.15	-0.75**	0.49*	-0.31	-0.15	-0.11	-0.26	-0.24
BD	-0.02	-0.84***	0.64*	-0.49*	-0.02	-0.29	-0.37	-0.39
TP	-0.01	0.81***	-0.63*	0.49*	-0.01	0.29	0.37	0.39
SOM	0.23	0.81***	-0.56*	0.61*	0.23	0.12	0.30	0.26
CEC	0.53*	0.56*	-0.32	0.68**	0.53*	-0.16	-0.27	0.03

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, grey values for non significant correlations.
AWC = available water content/capacity; SWS = soil water storage; SWD = soil water deficit; SWP = soil water surplus; AWP = available water for planting; DBH = diameter at breast height; SH = stand height; MAI = mean annual increment; PET = potential evapotranspiration; PD = soil particle density; BD = soil bulk density; TP = total porosity; SOM = soil organic matter; CEC = cation-exchange capacity.

factor can be then called as “favorable edaphoclimatic conditions for plant/stand development”. The last factor (F3; 12% of the variance, Fig. 5c) showed the “influence of climate on soil water and physical features”. Indeed, with increasing mean annual rainfall (Pmean), finer fractions (silt) in soil increased (alteration processes), thus increasing SOM and, consequently (increase in colloidal organic fractions), CEC; as previously explained, with these soil conditions, soil water increased (SWS) while issues in soil water deficit were mitigated (SWD).

On the whole, this research outlined the pivotal role played by soil development for *Eucalyptus* commercial plantation. In Fig. 6 the mean stand height, measured in each of the 14 investigated sites at the end of a complete rotation cycle, was compared to soil development. It is clear that at increasing soil development, i.e., from poorly developed sandy Entisols (E), to medium developed Inceptisols (I), till to most developed finer textured Oxisols (O), stand height performances greatly improved accordingly. As a matter of fact, the ANOVA revealed significant statistical differences ($p < 0.05$) between Entisol *vs* Oxisols in terms of: *i*) mean plant diameter with 12.2 cm in Entisols, while 13.6 cm in Oxisols; and *ii*) stand height, with 28.0 m in Entisols while 31.9 m in Oxisols. Consequently, even the wood mean annual increment at the end of a complete rotation cycle was strongly affected, being 46.7 $m^3\,ha^{-1}\,year^{-1}$ in Oxisols while 32.1 $m^3\,ha^{-1}\,year^{-1}$ in Entisols, meaning that in firts MAI was superior by 46%, as compared to the later.

4. Conclusions

For the first time, the maximum depth reached by a plastic clone of *E. urophylla* in a commercial plantation after a complete rotation cycle of 6 years was measured at about 16 m.

The investigation of the fine root system down to a depth of 20 m in a chronosequence series of 3, 9, 24, 48, and 65 months, showed a fast displacement of the root front to very deep soil layers. Deep roots can be relatively more efficient for acquiring soil water than shallow roots. Proportional water capture (PWC) was higher than generally expected in the deep soil layers, with values showing the importance of water uptake by the fine roots in the deep horizons. PWC was about 40% at a depth of 11 m at the age of 4 years and about 30% at a depth of 14 m at the age of 5.5 years.

Edaphoclimatic conditions play a major role in plant/stand development and behavior, with the “soil development” strongly dominating observed variability. Indeed, along the pedosequence Entisols → Inceptisols → Oxisols both plant and stand performances statistically improved. This shows that soil type and its development, together with other environmental factors, are likely to shape the vertical development and behavior of *Eucalyptus* plantation.

The mean annual increment at the age of 6 years was 46% higher in the Oxisols than in the Entisols in our study. A global investigation on whole soil features is needed to improve our understanting of the productivity of commercial *Eucalyptus* stands and to adapt management practices to climate changes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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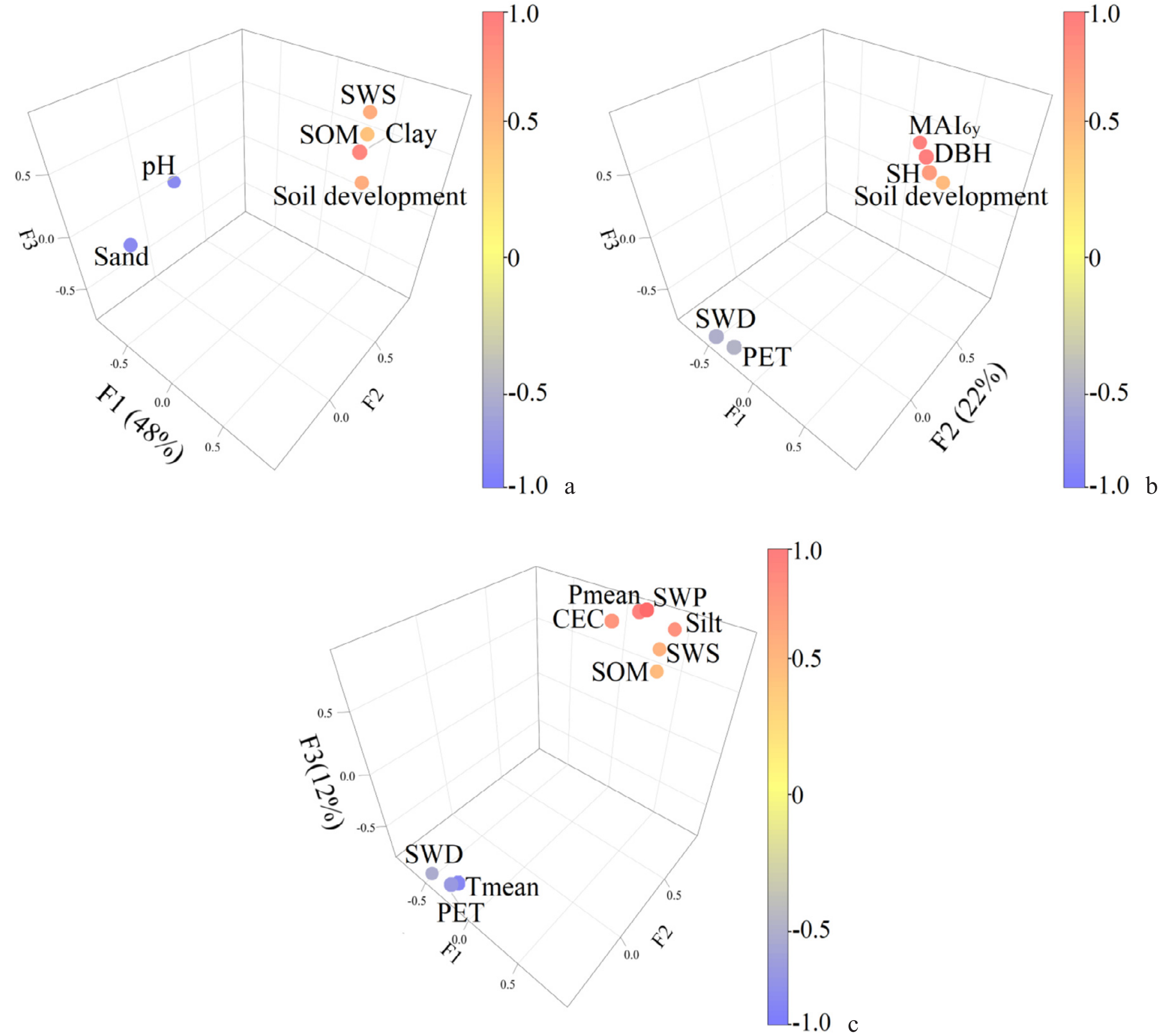

Fig. 5. 3D plots of a factor analysis; extraction method: principal factor analysis (PFA); rotation method: varimax; significance at $p < 0.05$.

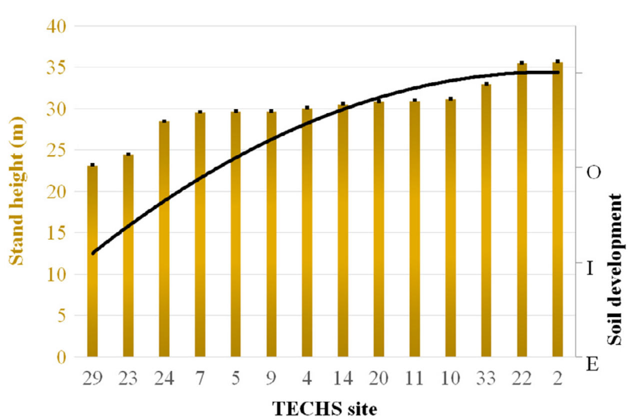

Fig. 6. Comparison between mean stand height (bars in brown color, scale on the left y-axis) *vs* soil development (line in black color, labels in the right y-axis) at the end of a complete rotation cycle in the 14 investigated sites. E = Entisols, I = Inceptisols, and O = Oxisols. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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References

ABNT – Associação Brasileira de Normas Técnicas, 2003. NBR 11941-02 – Determinação da densidade básica em madeira. ABNT, Rio de Janeiro.

Abreu-Junior, C.H., Firme, L.P., Maldonado, C.A.B., Moraes Neto, S.P., Alves, M.C., Muraoka, T., Boaretto, A.E., Gava, J.L., He, Z., Nogueira, T.A.R., Capra, G.F., 2017. Fertilization using sewage sludge in unfertile tropical soils increased wood production in *Eucalyptus* plantations. J. Environ. Manage. 203, 51–58. https://doi.org/10.1016/j.jenvman.2017.07.074.

Binkley, D., Campoe, O.C., Alvares, C., Carneiro, R.L., Cegatta, I., Stape, J.L., 2019. The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. For. Ecol. Manage. 405, 271–283. https://doi.org/10.1016/j.foreco.2017.09.050.

Buongiorno, J., Zhu, S., 2014. Assessing the impact of planted forests on the global forest economy. N. Z. J. For. Sci. 44 (Suppl. 1), S2. https://doi.org/10.1186/1179-5395-44-S1-S2.

Canadell, J., Zedler, P.H., 1995. Underground structures of woody plants in mediterranean ecosystems of Australia, California, and Chile. In: Arroyo, M.T.K., Zedler, P.H., Fox, M.D. (Eds.), Ecology and Biogeography of Mediterranean Ecosystems in Chile, California, and Australia. Springer, New York, pp. 177–210.

Capra, G.F., Coppola, E., Odierna, P., Grilli, E., Vacca, S., Buondonno, A., 2014. Occurrence and distribution of key potentially toxic elements (PTEs) in agricultural soils: a paradigmatic case study in an area affected by illegal landfills. J. Geochem. Explor. 145, 169–180. https://doi.org/10.1016/j.gexplo.2014.06.007.

Christina, M., le Maire, G., Nouvellon, Y., Vezy, R., Bordron, B., Battie-Laclau, P., Gonçalves, J.L.M., Delgado-Rojas, J.S., Bouillet, J.-P., Laclau, J.P., 2018. Simulating the effects of different potassium and water supply regimes on soil water content and water table depth over a rotation of a tropical *Eucalyptus grandis* plantation. For. Ecol. Manage. 418, 4–14. https://doi.org/10.1016/j.foreco.2017.12.048.

Christina, M., Nouvellon, Y., Laclau, J.-P., Stape, J.L., Bouillet, J.P., Lambais, G.R., le Maire, G., 2017. Importance of deep water uptake in tropical eucalypt forest. Funct. Ecol. 31, 509–519. https://doi.org/10.1111/1365-2435.12727.

Christina, M., Laclau, J.P., Gonçalves, J.L.M., Jourdan, C., Nouvellon, Y., Bouillet, J.P., 2011. Almost symmetrical vertical growth rates above and below ground in one of the world's most productive forests. Ecosphere 2, art27. https://doi.org/10.1890/ES10-00158.1.

da Silva, E.V., Bouillet, J.-P., de Moraes Gonçalves, J.L., Junior, C.H.A., Trivelin, P.C.O., Hinsinger, P., Jourdan, C., Nouvellon, Y., Stape, J.L., Laclau, J.P., 2011. Functional specialization of *Eucalyptus* fine roots: contrasting potential uptake rates for nitrogen, potassium and calcium tracers at varying soil depths. Funct. Ecol. 25, 996–1006. https://doi.org/10.1111/j.1365-2435.2011.01867.x.

Dye, P., 1996. Response of *Eucalyptus* grandis trees to soil water deficits. Tree Physiol. 16, 233–238. https://doi.org/10.1093/treephys/16.1-2.233.

Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA, 1997. Manual de Métodos de Análise do Solo. EMBRAPA, Rio de Janeiro.

FAO, 2019. Forestry Production and Trade. FAOSTAT, Rome (accessed 27.06.2017). http://www.fao.org/faostat/en/#data/FO/visualize.

Ferchaud, F., Vitte, G., Bornet, F., Strullu, L., Mary, B., 2015. Soil water uptake and root distribution of different perennial and annual bioenergy crops. Plant Soil 388, 307–322. https://doi.org/10.1007/s11104-014-2335-y.

Freycon, V., Wonkam, C., Fayolle, A., Laclau, J.P., Lucot, E., Jourdan, C., 2015. Tree roots can penetrate deeply in African semi-deciduous rain forests: evidence from two common soil types. J. Trop. Ecol. 31 (1), 13–23. https://doi.org/10.1017/S0266467414000595.

Germon, A., Jourdan, C., Bordron, B., Robin, A., Nouvellon, Y., Gonçalves, J.L.M., Chapuis-Lardy, L., Pradier, C., Guerrini, I.A., Laclau, J.-P., 2019. Consequences of clear-cutting and drought on fine roots dynamics down to 17 m in coppice-managed eucalypt plantations. For. Ecol. Manage. 445, 48–59. https://doi.org/10.1016/j.foreco.2019.05.010.

Gonçalves, J.L.M., 1995. Sistema radicular de absorção do *Eucalyptus* grandis sob diferentes condições edáficas. Silvicultura 17, 8–10.

Gregory, P.J., 2006. Roots, rhizosphere and soil: the route to a better understanding of soil science? Eur. J. Soil Sci. 57, 2–12. https://doi.org/10.1111/j.1365-2389.2005.00778.x.

IBÁ–Industria Brasileira de Árvores, 2017. Report 2017. IBÁ, Brasília Available at: https://www.iba.org/datafiles/publicacoes/pdf/iba-relatorioanual2017.pdf (accessed 25.06.2019).

Jackson, R.B., Sperry, J.S., Dawson, T.E., 2000. Root water uptake and transport: using physiological processes in global predictions. Trends Plant Sci. 5, 482–488. https://doi.org/10.1016/S1360-1385(00)01766-0.

King, J., Gay, A., Sylvester-Bradley, R., Bingham, I., Foulkes, J., Gregory, P., Robinson, D., 2003. Modelling cereal root systems for water and nitrogen capture: towards an economic optimum. Ann. Bot. 91, 383–390. https://doi.org/10.1093/aob/mcg033.

Köppen, W., 1936. Das geographische System der Klimate. Handbuch der Klimatologie, vol. 1.

Laclau, J.P., Silva, E.A., Lambais, G., Bernoux, M., Le Maire, G., Stape, J.L., Bouillet, J.P., Gonçalves, J.L.M., Jourdan, C., Nouvellon, Y., 2013. Dynamics of soil exploration by fine roots down to a depth of 10 m in *Eucalyptus grandis* plantations. Front. Plant Sci. 4, 243. https://doi.org/10.3389/fpls.2013.00243.

Lambais, G.R., Jourdan, C., Piccolo, M.C., Germon, A., Pinheiro, R.C., Nouvellon, Y., Stape, J.L., Campoe, O.C., Robin, A., Bouillet, J.P., le Maire, G., Laclau, J.P., 2017. Contrasting phenology of *Eucalyptus* grandis fine roots in upper and very deep soil layers in Brazil. Plant Soil 421, 301–318. https://doi.org/10.1007/s11104-017-3460-1.

Markewitz, D., Devine, S., Davidson, E.A., Brando, P., Nepstad, D.C., 2010. Soil moisture depletion under simulated drought in the Amazon: impacts on deep root uptake. New Phytol. 187, 592–607. https://doi.org/10.1111/j.1469-8137.2010.03391.x.

Monteith, J.L., 1965. Evaporation and environment. In: Fogg, G.E. (Ed.), Symposium of the Society for Experimental Biology, The State and Movement of Water in Living Organisms. Academic Press Inc, New York, pp. 205–234.

Nepal, P., Korhonen, J., Prestemon, J.P., Cubbage, F.W., 2019. Projecting global planted forest area developments and the associated impacts on global forest product markets. J. Environ. Manage. 240, 421–430. https://doi.org/10.1016/j.jenvman.2019.03.126.

Padilla, F.M., Pugnaire, F.I., 2007. Rooting depth and soil moisture control Mediterranean woody seedling survival during drought. Funct. Ecol. 21, 489–495. https://doi.org/10.1111/j.1365-2435.2007.01267.x.

Paz, H., 2003. Root/shoot allocation and root architecture in seedlings: variation among forest sites, microhabitats, and ecological groups. Biotropica 35, 318–332. https://doi.org/10.1111/j.1744-7429.2003.tb00586.x.

Pinheiro, R.C., de Deus, J.C., Nouvellon, Y., Campoe, O.C., Stape, J.L., Alò, L.L., Guerrini, I.A., Jourdan, C., Laclaua, J.P., 2016. A fast exploration of very deep soil layers by *Eucalyptus* seedlings and clones in Brazil. For. Ecol. Manage. 366, 143–152. https://doi.org/10.1016/j.foreco.2016.02.012.

Pienaar, L.V., Turnbull, K.J., 1973. The Chapman-Richards generalization of von Bertalanffy's growth model for basal area growth and yield in even-aged stands. For. Sci. 19, 2–22. https://doi.org/10.1093/forestscience/19.1.2.

Pierik, R., Testerink, C., 2014. The art of being flexible: how to escape from shade, salt, and drought. Plant Physiol. 166, 5–22. https://doi.org/10.1104/pp.114.239160.

Plasencia, A., Soler, M., Dupas, A., Ladouce, N., Silva-Martins, G., Martinez, Y., Lapierre, C., Franche, C., Truchet, I., Grima-Pettenati, J., 2016. Eucalyptus hairy roots, a fast, efficient and versatile tool to explore function and expression of genes involved in wood formation. Plant Biotechnol. J. 14, 1381–1393. https://doi.org/10.1111/pbi.12502.

Robertson, M.J., Fukai, S., Ludlow, M.M., Hammer, G.L., 1993. Water extraction by grain-sorghum in a sub-humid environment. 1. Analysis of the water extraction pattern. Field Crop Res. 33, 81–97. https://doi.org/10.1016/0378-4290(93)90095-5.

Robinson, N., Harper, R.J., Smettem, K.R.J., 2006. Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. Plant Soil 286, 141–151. https://doi.org/10.1007/s11104-006-9032-4.

Rolim, G.S., Sentelhas, P.C., Barbieri, V., 1998. Planilhas no ambiente EXCELTM para os cálculos de balanços hídricos: normal, seqüencial, de cultura e de produtividade real e potencial. Rev. Bras. Agrometeorol. 6, 133–137.

RStudio Team, 2016. RStudio: Integrated Development for R. URL. RStudio, Inc., Boston, MA. http://www.rstudio.com/.

Schenk, H.J., Jackson, R.B., 2002. The global biogeography of roots. Ecol. Monogr. 2, 311–328. https://doi.org/10.1890/0012-9615(2002)072[0311:TGBOR]2.0.CO;2.

Smethurst, P.J., Almeida, A.C., Loos, R.A., 2015. Stream flow unaffected by *Eucalyptus* plantation harvesting implicates water use by the native forest streamside reserve. J. Hydrol. Reg. Stud. 3, 187–198. https://doi.org/10.1016/j.ejrh.2014.11.002.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stape, J.L., Binkley, D., Ryan, M.G., Fonseca, S., Loos, R.A., Takahashi, E.N., Silva, C.R., Silva, S.R., Hakamada, R.E., Ferreira, J.M.A., Lima, A.M.N., Gava, J.L., Leite, F.P., Andrade, H.B., Alves, J.M., Silva, G.G.C., Azevedo, M.R., 2010. The Brazil *Eucalyptus* potential productivity project: influence of water, nutrients and stand uniformity on wood production. For. Ecol. Manage. 259, 1684–1694. https://doi.org/10.1016/j.foreco.2010.01.012.

Wingfield, M.J., Roux, J., Slippers, B., Hurley, B.P., Garnas, J., Myburg, A.A., Wingfield, B.D., 2013. Established and new technologies reduce increasing pest and pathogen threats to Eucalypt plantations. For. Ecol. Manage. 301, 35–42. https://doi.org/10.1016/j.foreco.2012.09.002.

Witschoreck, R., Schumacher, M.V., Caldeira, M.V.W., 2003. Estimativa da biomassa e do comprimento de raízes finas em *Eucalyptus urophylla* S.T. Blake no município de Santa Maria-RS. Rev. Árvore 27, 177–183. https://doi.org/10.1590/S0100-67622003000200008.

Zhang, X., Pei, D., Chen, S., 2004. Root growth and soil water utilization of winter wheat in the North China Plain. Hydrol. Process. 18, 2275–2287. https://doi.org/10.1002/hyp.5533.